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Improving the performance of water balance equation using fuzzy logic approach

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SUMMARY

It is a common practice to conduct the water budget or water balance analysis in a given area within a specified time in order to investigate the balance between the inputs and outputs of the water system. Such an analysis can be used for water management and water allocation in a designated study area. Due to appearance of an error in water balance equation because of difficulty in accurate estimation of its individual components, the main objective of the current paper was to apply a set of fuzzy coefficients to the components of the water balance equation in order to reduce this error. The fuzzy coefficients reflect the uncertainty and imprecision in evaluating each component, and minimize the overall error of the water balance equation. These coefficients are adjusted by an error minimization procedure, based on fuzzy regression concepts and using available recorded data for a given study area within a specified time scale. The adjusted coefficients can effectively estimate the water balance components in the future. In this study, four different models, representing different types of fuzzy coefficients, were considered and used for annual water balance of Azghand catchment in Khorasan Razavi Province, Iran as a case study. Analysis of results showed that all models were effective in reducing water balance error in Azghand catchment. The best model reduced the error up to 79% in terms of mean absolute error compared with error in water balance equation when conventional (with no correction coefficients) water balance analysis was conducted. Moreover, the results indicated that the performance of the proposed fuzzy models was not significantly sensitive to selection of confidence level in data (h) and improved slightly as h increased.

1. Introduction

Due to high demand of water in developed societies, precise strategies are required to manage water resources in order to achieve optimized patterns for distribution and consumption. Water resources planning for future consumption requires precise data, however managers and experts usually encounter an unavoidable challenge known as uncertainty in the field of hydrology.

In hydrological modeling, uncertainty may have two sources: (1) structural uncertainty, and (2) parameter uncertainty. Structural uncertainty is associated with uncertain cognition of the overall functioning of any hydrological system and the uncertainty in the model structures used for modeling the system. Parameter uncertainty is related to the uncertainty of the inputs and parameters of a model (Eder et al., 2005).

Water balance is one of the fundamental principles in water resources management and hydrology. There are many methods of balancing water in different temporal and spatial scales. In fact, the water balance study is the hydrological application of the principle of conservation of mass for water, namely the continuity equation (Sokolov and Chapman, 1974). Study of groundwater, surface water, and storage variations are also dependent on the results of water balance analysis in an aquifer or catchment (Todd and Mays, 2005).

The uncertainty, vagueness, and inaccuracy of hydrologic data result from errors of measurement equipments and estimation models. Therefore, random or epistemic errors are present in the water balance equations results. These errors indicate that water balance studies are fairly unreliable and therefore water allocations using hydrologic data can also be inaccurate for the future studies. Accuracy of the studies can be improved in many cases through upgrading, replacing or adding the equipment and methods required to collect and process the data, however it especially

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might be time-consuming and costly in countries with budget limitation. Enhancing the accuracy of water balance equations through increasing the efficiency of computational methods can fairly alleviate unreliability concern.

Fuzzy logic proposed by Zadeh (1965) is a powerful approach that has been successfully applied to various fields of science and engineering which deal with inaccurate data. Probability theory can determine the likelihood of an event, however it may not be capable to identify the uncertainty originated from vagueness in input data, parameters, and system behavior. In order to solve this problem, possibility theory using fuzzy numbers instead of crisp numbers can capture vagueness in system parameters or its complexity. In other words, fuzzy numbers can express imprecise, vague, intuitive, inconsistent, experimental, or subjective information in the form of uncertainty that can be used in fuzzy modeling (Zadeh, 1978). Several approaches have been developed based on fuzzy set theory (Zadeh, 1978, 1986; Dubois and Prade, 1994; Yager and Kelman, 1996) to model uncertainty of phenomena (Faybishenko, 2010).

Fuzzy modeling has been applied to several problems in hydrology (Bogardi et al., 1983; Bardossy and Disse, 1993; Ozelkan and Duckstein, 2001; Luchetta and Manetti, 2003; Maskey et al., 2004; Shrestha and Rode, 2008; Guler et al., 2012) and water resources management (Esogbue et al., 1992; Sutardi et al., 1995; Wu et al., 1997; Bender and Simonovic, 2000; Chang, 2005; Li et al., 2009; Wang and Huang, 2011) for modeling uncertainty of hydrological events or phenomena. However, Bardossy (1996) studied application of fuzzy logic in modeling water cycle for the first time. He used a fuzzy rule-based methodology to describe three elements of the hydrological cycle: surface runoff, infiltration, and unsaturated flow of water in soil.

Eder et al. (2005) presented a formulation for a lumped water balance model based on fuzzy logic in Upper Enns catchment in Austria and evaluated the efficiency of fuzzy logic approach in modeling the system complexity, predictive uncertainty and accuracy of predictions. In another study, Faybishenko (2010) studied water balance uncertainty using fuzzy probabilistic approach in Hanford site in USA. He combined the probability and possibility theories to model the soil water balance and assessed the associated uncertainty in the components of the water balance equation. Nasseri et al. (2013) proposed a new method based on fuzzy extension principle to assess uncertainty of the water balance models. They calibrated two non-linear monthly water balance models for two catchments in Iran and France. The results were compared with those of five different models. The suggested models showed well performance in uncertainty analysis of water balance model in all selected levels of confidence. In a more recent study, Nasseri et al. (2014) suggested a hybrid fuzzy-probabilistic model for monthly prediction or simulation of hydrological components in water balance equation. The suggested methodology was used to simulate stream flows of Roudzard and Karoon III basins in South-West of Iran.

For long, linear regression analysis has been used to analyze hydrological problems with the main objective of developing predictive equations by minimizing the deviations of the estimated values from the corresponding observed values. Fuzzy linear regression analysis proposed by Tanaka et al. (1982) is based on the linear programming formulation. It interprets these deviations as the indefiniteness of the system structure and fuzziness of system parameters. The objective of this type of fuzzy regression models is to minimize the fuzziness of a system in which fuzzy parameters follow a possibility distribution. Different versions of fuzzy regression models based on possibility theory have been introduced by Tanaka et al. (1989), Bardossy (1990) and Bardossy et al. (1990) trying to resolve some of the defects of the Tanaka et al.'s approach.

Tanaka et al.'s model has also been modified to determine the fuzzy coefficients of fuzzy linear relationship based on the least square approach (Celmins, 1987; Savic and Pedrycz, 1991; Tanaka and Ishibuchi, 1991; Chang and Ayyub, 1997). The other type of fuzzy regression is based on interval analysis, only requiring that in each degree of uncertainty, each predicted interval to intersect the associated observed interval of data (Peters, 1994; Ozelkan and Duckstein, 2000; Sakawa and Yano, 2000; Hojati et al., 2005).

The objective of this study was to apply a set of fuzzy coefficients to different components of water balance equation in order to minimize the existing error in water balance equation. The two following models were applied: fuzzy regression models based on possibility theory and fuzzy regression models based on interval analysis. Applying the error minimization procedure to a set of available data in each model, adjusts the fuzzy coefficients in the water balance equation. In the current case study, four models were generally developed and compared on water balance data of Azghand catchment in Khorasan Razavi Province, Iran. The models are presented and explained in the methodology section.

2. Background on fuzzy numbers and fuzzy linear regression models used in this study

2.1. Fuzziness and fuzzy numbers

The term fuzziness is generally referred to the class of objects or processes without sharp boundaries that may result from imprecision in definitions, estimations or measurements in order to model the system. Fuzzification of crisp values results in fuzzy numbers, which are expressed in the shape of fuzzy membership functions that can assign different intervals to a definition in different degrees of its membership. These intervals are defined by the information taken from measurements, intuition or perception of the parameter in the study. The most significant role of fuzzy numbers in possibility theory is the ability of expressing uncertainty of real values and crisp numbers in phenomena and providing a fuzzy set in R that arithmetic or algebraic operations can easily be performed (Zadeh, 1978, 2002).

Different shapes of fuzzy membership functions including triangular, trapezoidal, Gaussian, and sigmoid are commonly used to represent a fuzzy number. However, the triangular fuzzy number is one of the most widely used types in fuzzy mathematics. It is formulated as (Wang, 1997; Ross, 2004; Moller and Beer, 2004):

$$\mu_{\tilde{A}}(x) = \begin{cases} (x-a)/(b-a), & a \leqslant x < b \\ (c-x)/(c-b), & b \leqslant x < c \\ 0, & x > c \text{ or } x < a \end{cases} \quad (1)$$

where $\mu_{\tilde{A}}(x)$ denotes membership degree of element x to set $\tilde{A}$ and a, b and c are left, center and right values of triangular membership

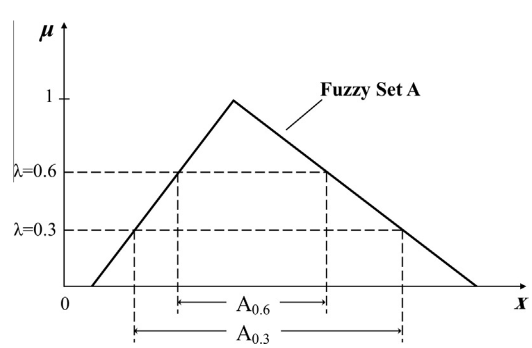

Fig. 1. Different λ-cut sets for a triangular fuzzy number (Ross, 2004).